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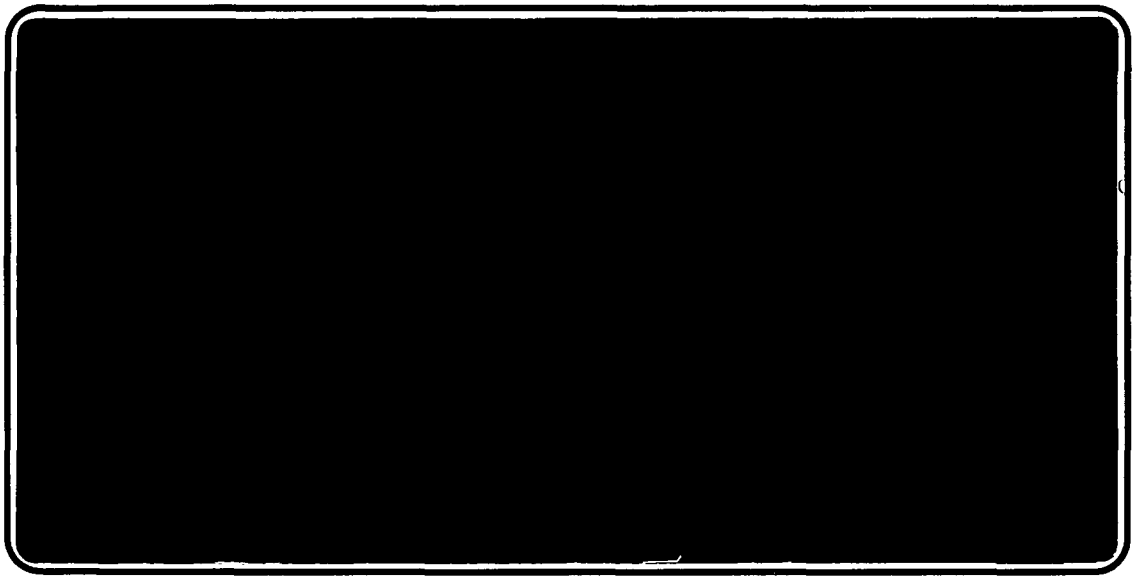

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STRENGTH IMPROVEMENT THROUGH REFINING AND WET PRESSING

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Strength Development Through Refining and Wet Pressing

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ABSTRACT

At a given level of sheet densification, it is usually found that refining and wet pressing yield a higher tensile strength than wet pressing alone. An attempt was therefore made to examine this behavior within the framework of linear elastic fracture mechanics. It was hypothesized that at a given level of densification, differences in pore size distribution would be evident, and that this would be a factor in strength development, i.e., the larger pores would give rise to greater stress concentration or critical crack size.

For northern and southern pine handsheets which had been subjected to different levels of refining and wet pressing, a property density envelope was found for in-plane elastic constant, fracture resistance, pore size at maximum frequency, tensile strength, and notched tensile strength.

Although a correlation of the data based on Griffith's equation was not successful, a good correlation was found between specific tensile strength σ^* and the product of specific fracture resistance G_c^* and specific modulus E^* of the form $\sigma^* = A(E^*G_c^*)^n$. This relationship seems to imply that tensile strength is not dependent on crack size. However, tensile strength does show a sensitivity to single-edge notches particularly at the highest level of refining.

Estimates of crack size using fracture resistance, modulus, and tensile data was found to be in the range of 1 mm to 2.5 mm. This might be interpreted as a formation effect. Crack tortuosity is one indication that formation might be an important factor. Curiously, the size, shape, and distribution of the pores did not appear to be important factors.

INTRODUCTION

Refining and wet pressing are important process steps of papermaking. The primary function of refining is to modify the structure of the fibers in order to enhance their papermaking potential, while wet pressing removes water and consolidates the web prior to drying. In this paper, we will consider how the tensile strength of paper is influenced by refining and wet pressing.

Generally, at a given level of bonding or sheet densification, refining will produce a paper having a higher tensile strength than one which has only been wet pressed. This is illustrated in Figure 1 using the data of Rennel (1).

A satisfactory explanation for this difference has yet to be given. Although refining offers positive benefits to the papermaking process, it nevertheless has an adverse effect on water removal. In contrast, wet pressing is viewed as an effective means of removing water mechanically, and as a consequence, many of the strength properties of the sheet are enhanced. A better understanding of strength development by refining and wet pressing may therefore lead to the achievement of a better balance between these processes in order to better optimize strength properties and productivity. Is it possible that some grades of paper may be made with little or no refining if the water removal and consolidation process can be improved?

Fracture mechanics is the main approach we have employed toward an understanding of this problem. In other areas of material science, a common goal is to understand the nature of flaws and stress concentration. This has lead to strength improvements in such materials as glasses, polymers, cement, and composites.

LITERATURE REVIEW

In standard pulp evaluation procedures, refining is usually the only papermaking process variable which is varied although there are a number of studies in the literature where both refining and wet pressing have been varied, e.g., (1-3). In most cases, we typically see the tensile strength versus density or bond area envelope shown in Figure 1.

A number of theories have been developed for predicting the tensile strength of paper (4-8) which have been reviewed by several authors (6-8). Page's (4) equation, however, seems to be the one which is most often used to explain the tensile strength of paper. It involves six independent variables namely fiber strength, bond strength, fiber length, fiber perimeter, fiber coarseness, and relative bonded area.

The most problematical of these measurements are fiber strength (zero-span strength) and relative bonded area. Generally, zero-span measurements are dependent on fiber geometry and relative bonded area, and an extrapolation procedure may be necessary as proposed by Cowan (9) to determine a value independent of these effects. Furthermore, there is as yet no satisfactory way to determine the total unbonded surface area of fibers in a given state of bonding thus making relative bonded area determinations somewhat suspect. An evaluation of Page's equation by Waterhouse (7) for a variety of pulps using Rennel's data gave very mixed results.

A graphical interpretation of Page's equation is shown in Figure 2. This interpretation assumes that wet pressing only changes relative bonded area. When

refining is changed, then according to Figure 2, this may result in increases in both bond strength and fiber strength (zero-span strength).

Single interfiber bond studies namely Stratton (10) and Mohlin (11) have shown that specific bond strength does not change with refining, while the work of McIntosh (12), Button (13), Stratton (10), Hieta et al. (14) suggests that bond strength may be dependent on bond geometry, i.e., the results of McIntosh and Stratton show that latewood fibers yield a higher interfiber bond strength than earlywood fibers. Of course, we have yet to determine if single interfiber bond strength results are relevant to paper. One problem with single interfiber bond tests which has not yet been addressed is the influence of fines although Nanko's (15) recent findings indicate that this might be an important consideration. Retulainen and Ebling (16) have evaluated a number of methods for measuring bond strength and found it to increase in some instances with refining.

Button (13) investigated the strength of lap joints using cellophane model fibers. He found that as the bond width to thickness ratio decreased, specific bond strength increased, and these findings were in close agreement with theoretical predictions based on linear elastic fracture mechanics, LEFM. It is interesting to speculate on whether these findings explain the strength differences between earlywood and latewood single interfiber bonds (12).

Bond strength changes due to wet pressing are less clear cut although the indications are that bond strength based on energy measurements is reduced according to the findings of Nordman (17) and Skowronski (18).

Increases in fiber strength due to refining have been found by a number of researchers including Alexander and Marton (3a) and Kim et al. (19). The increase is justified on the basis of increased fibril orientation and the reduction of cell-wall defects such as microcompressions which occur during restrained drying of the fiber.

Alexander and Marton (3a) also examined the effects of wet pressing on single earlywood and latewood fiber modulus and strength. It is difficult to draw general conclusions from their work since there is a complex interaction between refining and wet pressing producing different effects in earlywood and latewood fibers.

Tensile strength is also dependent on formation and as the uniformity in mass density deteriorates so does tensile strength. Presumably, Page's equation would interpret this as a loss in bonding strength, although loss of uniformity suggests an increase in stress concentration within the network.

In summary, Page's equation suggests that refining and wet pressing may be more effective in improving strength than wet pressing alone since both fiber and interfiber bond strength may be improved by refining, while wet pressing alone may actually reduce interfiber bond strength. Nevertheless, bond strength remains something of an enigma since there is some contradiction between the inferences made from network and single interfiber bond strength determinations.

A tensile strength model for paper where it is viewed as a voidal continuum has also been proposed by Waterhouse (7) and is illustrated in Figure 3. We note that as the network is densified by various combinations of refining and wet pressing, its strength approaches a common level at a density close to the density of the cell wall, i.e., 1.55 g/cm^3 for cellulose. The interesting question which arises is how do we explain the difference in strength at a given level of density or solidity?

At a given level of densification, we have the same void volume irrespective of how it was produced. However, there must be a difference in size and shape of the pores constituting that void volume. Furthermore, these dissimilarities may result in stress concentration differences which could be responsible for the strength difference found. Dissimilarities in pore size, shape, and distribution should, at the appropriate level of resolution, result in differences in mass density distribution.

For brittle materials such as glass, cement, some metals and polymers, the ideas of fracture mechanics have been used to examine the impact of flaws or defects on their ultimate strength. It has been shown that when these defects are eliminated or reduced in size, the strength of the material can be greatly enhanced. The classical Griffith equation for tensile strength, equation 1, shows that strength deteriorates as the inverse square root of the critical crack or flaw size,

$$\sigma = [(E \times G_c)/(\pi \times c)]^{0.5} \qquad (1)$$

where E is the modulus of the material, G_c the fracture toughness, and c the critical crack size.

The application of equation 1 to the improvement of cement strength, known as defect-free cement, has been the subject of a number of recent papers, e.g., see Birchall et al. (20). The relationship between strength and crack size for cement taken from Birchall et al. is shown in Figure 4.

Nissan (21) was one of the first researchers to apply fracture mechanics to paper and to conclude that LEFM was not applicable to paper. Since that time there have been a number of papers and reviews (22-33) on the subject where consideration has been given to such topics as whether paper may be treated as a brittle material, its fracture behavior when gross flaws such as edge cuts are present, measurement of fracture resistance for both regular and very tough papers (*J. Integral Techniques*), and measurement of out-of-plane fracture resistance.

Specific fracture toughness G* measurements made by a number of researchers using a variety of techniques are summarized in Table 1.

Table 1: Published Fracture Toughness Results

Author	Paper	Grammage g/m^2	Density g/m^3	G* Jm/g
Andersson & Falk (24)	sack	80		0.015
	MG kraft	80		0.318
	normal #3	120		0.0054
	newsprint	52		0.0059
Balodis (23)	eucalyptus kraft (9 mm crack)	60	(0.7)	0.0028
	eucalyptus kraft (3 mm crack)	60	(0.7)	0.0014
Brezinski (27)	web offset	49		
	(3 mm crack)			0.00093
	100 mm crack)			0.00259
	bond paper	74		
	(3.15 mm crack)			0.0010
	(100 mm crack)			0.0020
Corte*	bl. spruce sulfite	81		0.0278
Jensen**	bl. kraft D. Fir	60	0.419	0.00289
	fiber length 1.19 mm		0.633	0.00344
	fiber length 1.91 mm		0.405	0.00496
			0.597	0.00662
Seth & Page (26)	bond paper	73	0.726	0.0108
	unbl. kraft	49	0.817	0.0370
	semibl. kraft	44	0.562	0.0309
Steadman & Fellers (29)	unbl. sack kraft	60		0.0173
				0.0237

*H. Corte, H. Schaschek, and O. Broens, *TAPPI* 40(6):441-447(1957).

**J. R. Jensen, "Effect of Fiber Length and Sheet Density on the Fracture Resistance of Paper," M.S. Thesis, U. of Washington (1983).

The two principal techniques involve using large edge or center cracked specimens in the tensile mode or the measurement of a quasi-steady fracture propagation using massive jaws where only sufficient energy is supplied to produce fracture propagation. Seth and Page (25) have shown that under the right conditions these two approaches are equivalent. Techniques involving more conventional tensile testing of samples with either edge or center cracks appear to have much lower values of fracture resistance, e.g., see Balodis (23).

EXPERIMENTAL

Pulps and Handsheet Making

The two low-yield softwood bleached kraft pulps used in this study were a northern pine and a southern pine. The pulps were never dried and were thickened to 30 to 35% consistency and were stored with formaldehyde in the cold room at 4°C until required.

The pulps were beaten in a PFI mill using a gap setting of 0.4 mm, and a series of runs were made to provide sufficient pulp for sheetmaking in the Formette Dynamique. The two refining levels were 0 revs and 9000 revs. The unrefined pulp was treated in a British disintegrator for five minutes to ensure proper pulp dispersion, while the refined pulp was treated for three minutes. Following disintegration the pulps were diluted to 0.5% consistency in preparation for sheetmaking. The average Canadian Standard Freeness values for the different batches of pulp are given in Table 2.

Table 2: Freeness Values of Refined Pulps

Pulp Type	Grammage*	0 revs	9000 revs
Northern Pine	200	679	240-216
	100		249-222
Southern Pine	100	650	170

*Northern Pine handsheets were made at two grammage levels.

Handsheets having close to a random orientation of fibers were made on the Formette Dynamique (34) using an H 1/4 U2510 nozzle and a wire speed of 820 meters/min. After forming, the handsheets were centrifuged by increasing the wire speed to 1900 meters/min which resulted in a couched solids of approximately 23%. After forming and couching, the handsheets were lightly marked with indelible pencils a known distance apart. The spacing between these marks was checked after pressing and drying in order to detect any changes in sheet dimensions. Following this procedure the sheets were placed between wet blotters of approximately the same consistency and stored in the cold room to await pressing and drying.

We wished to achieve, by refining and wet pressing, high levels of densification, i.e., around 1 g/cm^3 and at the same time maintain complete restraint until the sheet is dry. The traditional separation of wet pressing and drying which is used for handsheet preparation is not satisfactory for this purpose. In press drying, Setterholm and Kuenzi (35) showed that once water is removed to below the fiber saturation point then restraint on the sheet is required until it is fully dry to prevent shrinkage. It was found that when pressing to a high solids content, pressing and drying can no longer be separated. In order to achieve the required restraint

conditions during wet pressing and drying, two methods were used as discussed by the authors in a recent presentation (36).

The method used for restraint during pressing and drying of the northern pine 200 g/m^2 handsheets is shown in Figure 5.

A 19 cm square handsheet cut from the Formette handsheet (91 cm x 21.6 cm) is placed on the solid backing plate A, Figure 5. Six blotters are placed on top of the handsheet, the first of which is treated with a silicone release agent to prevent sticking or bonding particularly at high levels of densification. A forming wire is then placed on the top blotter to allow easy removal of the center plate C. The center plate C is then installed, and a large aluminum block is placed on top to allow easy access to the clamping screws during the pressing operation. The assembly is then placed in the Baldwin press which is programmed to achieve the desired loading in about 45 to 60 seconds. The peak load was maintained for 10 minutes to allow sufficient time for the outer ring clamp to be tightened and ensure reproducibility of the pressing procedure. The screws were finally tightened using a torque wrench to 27.1 Nm (20 ft lbs force).

After the press cycle was completed and the restraint apparatus removed from the press, the center plate and blotters were also removed, and the sheet was allowed to air dry for 24 hrs at 73°F and 20% RH. The sheet was then released from the restraint device and stored at 73°F and 50% RH.

The second method used for continuous restraint during pressing and drying was the IPST press and dryer combination shown in Figure 6.

This method is used to press and dry full-size Formette handsheets with minimal shrinkage. After couching, the sheet is placed between three blotters (one above and two below the sheet) and placed on the moving dryer felt just prior to the press nip. After this sandwich has passed through the press nip the press is stopped, and the sheet is dried under full restraint against the dryer drum surface for 30 mins at 90°C. Although this method does not completely restrain the sheet at the highest levels of densification, the loss in elastic properties is small (36). After pressing and drying, the sheets are first pre-conditioned and then conditioned following TAPPI recommended procedures.

Nondestructive Testing

Nondestructive characterization of the handsheets consisted of measuring changes in sheet dimensions, hard and soft platen calipers (37), grammage, and in-plane and out-of-plane elastic constants using ultrasonic wave propagation techniques developed at IPST (38-39).

Fracture Resistance

Fracture resistance measurements are based upon the quasi-static method proposed by Gurney and Hunt (40) and later used by Seth and Page (25) to measure the fracture

resistance of paper. A rigid clamping system is required to keep the clamps parallel to each other and ensure a pure mode I fracture. Also, the stored elastic energy has to be small so that catastrophic failure is avoided and only energy is consumed in fracture.

A modified IPST in-plane tear tester (41) shown in Figure 7 was used to perform these tests. Normally, the jaws of this tester are rotated through 6^{o}, but for the purposes of having a pure mode I fracture they were kept at 0^{o}. Seth and Page (42) have indicated that this should give agreement with their method. The double-edged notch (DEN) sample geometry and dimensions are given in Figure 8.

A cross-head speed of 0.254 mm/min (0.01 inches per minute), corresponding to a strain rate of 1.2%/minute was used. Although the sample geometry is very similar to that used by Seth and Page (26), one major difference is that their samples are about twice the size of ours, i.e., 4 cm x 15 cm versus 2.1 cm x 6.3 cm, respectively. Sample size can be important in determining the stress level at which quasi-static crack propagation occurs.

It is generally found that after the fracture test is complete the two sample halves are still held together by fibers bridging the gap. An estimate of the energy required to pullout these fibers was also measured.

The fracture energy was measured from the appropriate areas under the load-displacement curve which is sketched in Figure 9.

In Figure 9, area A corresponds to the irreversible plastic deformation which occurs prior to crack propagation, and area B is that amount of elastic energy stored in the sheet at the onset of fracture. Area C is the additional energy required to complete fracture, and area D is the additional amount of energy required to pull fibers out of the network after fracture has been completed.

The energy involved in fracture is calculated from the sum of the areas A and B. The fracture resistance R multiplied by the sheet thickness t is obtained by dividing the energy of fracture by the crack length (units of J/m). The specific fracture resistance is obtained by dividing this quantity by the sample grammage. The crack tortuosity factor is defined as the ratio of the actual to geometric crack length, i.e., 37 mm (see Figure 8). This factor appears to depend on formation, for example, trials with cellophane gave a tortuosity factor of 1.0, scratch pad paper 1.35, and Formette handsheets 1.1.

Mercury Porosimetry

Pore size distribution of the 200 g/m^2 handsheets was measured using an American Instrument Company Porosimeter, model 5-7121, 0-103 MPa (0-15,000 psi) range.

Tensile and Notched Tensile Testing

Tensile testing of the 100 g/m^2 handsheets was done using rectangular samples 127 mm x 25.4 mm and a cross-head speed of 12.7 mm/min. Sample slippage, even with line clamps, was experienced when testing the 200 g/m^2 handsheets; therefore, dogbone-shaped tensile samples were used. The test section of the dogbone-shaped samples measured 58.9 mm x 12.7 mm, and the overall length of the samples was 114.3 mm.

Single-edge notched tensile tests were also performed on the 100 g/m^2 handsheets using rectangular samples 127 mm x 25.4 mm and a cross-head speed of 12.7 mm/min. The single-edge notch was cut with an X-Acto knife normal to the left-hand edge at mid-span of the tensile specimen. The notch sizes were 0, 0.51, 1.27, 2.54, 3.81, 6.35, 8.89, 10.16, and 12.7 mm.

RESULTS AND DISCUSSION

The variation of in-plane elastic properties, fracture resistance, median pore size, and tensile strength with densification by wet pressing at two levels of refining for the Northern Softwood 200 g/m^2 handsheets are shown in Figures 10, 12, 14, and 15.

We note that envelopes are formed for all of the above properties, i.e., the data do not form a single correlation independent of refining level.

According to Page and Seth (43), there are three basic mechanisms to account for the variation of mean in-plane specific elastic constant with apparent density shown in Figure 10. The first is that increasing densification at any level of refining will increase relative bonded area and thus reduce the fiber end effect. The second mechanism proposed is that the fiber's effective modulus is increased through fibril realignment, i.e., reduction of microcompressions. The reduction of gross kinks and curl, particularly in market pulps, and concomitant increase in load bearing fibers is the third mechanism proposed. No measurements of fiber curl or the frequency of microcompressions were made during this study. However, in view of the fact that the pulp was never dried, it is tentatively concluded that refining has produced an effective increase in fiber modulus.

The variation of out-of-plane specific elastic constant with apparent density is shown in Figure 11. An envelope in this property is much less distinct. A theoretical prediction for the out-of-plane elastic constant has been given by Berger (44) and is equal to the product of the fiber's transverse specific elastic constant multiplied by R.B.A. Therefore, if there is an increase in the out-of-plane specific elastic constant with refining at a given level of R.B.A., this would imply an increase in the transverse elastic constant of the fiber with refining.

There is a scarcity of data on the transverse elastic properties of fibers. Berger found that even with low levels of refining, the transverse stiffness of the fiber decreased, and attributed this to a loss of the fiber's primary and outer secondary wall layers.

We also see for a density greater than about 1 g/m^2 that there is a reduction in out-of-plane elastic constant. No satisfactory explanation can yet be given for this effect, although some form of damage is suspected, i.e., a calendaring effect.

A number of researchers have measured the fracture resistance of paper; however, the micromechanics of fracture have yet to receive attention, i.e., the role of fiber and interfiber bonding, etc. Such an understanding would be helpful in explaining the variation of fracture resistance with densification shown in Figure 12. It is seen that refining is more effective than wet pressing in increasing fracture resistance.

We have observed that there is a greater degree of fiber pullout at the lowest level of refining, while fiber failure is predominant at the highest level of refining. With reference to Figure 9 we have also found that the work of separation, i.e., area D, is also greater for the lowest level of refining as shown in Figure 13. This suggests that the basic mechanisms operative in fracture are similar to those controlling tensile failure as proposed by Page (4) and Kallmes (5), i.e., predominantly bond failure at low levels of refining progressing to predominantly fiber failure at high levels of refining.

The effect of refining and wet pressing on pore size at maximum frequency is shown in Figure 14. At a given level of densification, i.e., void volume, we see that increased refining results in a greater number of smaller pores. Since these pores are likely to be interfiber pores, then it follows that on average the size of interfiber bonds should be smaller. Therefore, following our earlier discussion of Button's (13) work, this should result in a reduction in stress concentration and an increase in interfiber bond strength.

The variation of tensile strength with apparent density is shown in Figure 15 for the northern pine 200 g/m^2 handsheets. We note that at constant density strength is improved by refining as found by other researchers, e.g. (1).

Acknowledging that conditions for brittle fracture may not be completely satisfied, we have, nevertheless, attempted to use Griffith's equation, i.e., equation 1 to reconcile tensile strength, modulus, fracture resistance, and pore size data. The relationship between tensile strength and the product of specific in-plane modulus E^* and fracture toughness G^* is shown in Figure 16 for the 200 g/m^2 handsheets. A good correlation is found which is given by,

$$\sigma^* = 2.73(E^*G^*)^{0.60} \qquad (R^2 = 0.99)$$

where σ^* is specific tensile stress.

This correlation is similar to that found by Waterhouse (7) using the data of Seth and Page for refining at a constant level of wet pressing for different pulps (the exponent was in the range of 0.67 to 0.8).

When pore size at maximum frequency is used as a measure of critical crack size c, i.e., (E^*G^*/c) and its variation with specific tensile stress is examined, a single correlation is no longer obtained.

Another way of using the data is to calculate the effective "crack" size using equation 1 or calculate fracture toughness assuming that the maximum frequency pore size is representative of crack size. Results for the 200g/m^2 northern pine handsheets are given in Table 3.

Table 3: Calculated Critical Crack Sizes and Fracture Toughness Values

Refining PFI Revs	Pressing KPa	Crack size m m	Fracture Toughness Jm/g X 10^6	Ratio Pred./Meas. 10^4
0	0	2.2	4.3	22
0	141	1.9	4.3	14
0	704	1.5	4.2	11
0	1410	1.3	2.9	6
0	2814	1.5	2.6	4
0	7036	1.3	2.1	3
9000	0	1.2	7.0	9
9000	0	1.1	6.1	9
9000	704	1.3	5.3	6
9000	1410	1.3	2.7	3
9000	2814	1.4	1.4	2
9000	7036	1.1	1.2	1

We see that the predicted crack size is in the range of 1.1 to 2.2 mm and that there is a small reduction in average crack size with refining. The predicted crack size is of course much larger than the pore size at maximum frequency. On the other hand, the values of predicted fracture toughness, assuming that the pore size at maximum frequency is representative of crack size, are much lower than measured as the ratio of predicted to measured values in Table 3.

We will defer further discussion on critical crack size and related issues until after results on notched tensile testing have been presented.

The data we have presented so far has been for northern pine 200g/m^2 handsheets where the tensile tests were performed using dogbone-shaped samples as stated previously in the experimental section. In order to determine notch sensitivity, tensile tests were performed using samples having a grammage of 100 g/m^2. The variation of specific tensile strength with notch size is shown in Figure 17 for the various levels of refining and wet pressing.

It is interesting to note the similarity between Figure 17 and Figure 4 which illustrates the notch sensitivity of cement found by Birchall (20). We observe that at the lowest level of refining and wet pressing, tensile strength is relatively insensitive to notch size. However, at the highest level of refining and wet pressing, the sensitivity of tensile strength to notch size is much greater, and there is less influence of wet pressing except in the unnotched samples.

The specific tensile strengths shown in Figure 17 are calculated on the basis of total sample width. In Figures 18 and 19, the extremes of refining and wet pressing are graphed on a log-log scale and include calculations based on load bearing area, i.e., sample width minus crack width. We see that even when specific strength is based on load bearing area, there is still a reduction in strength. This indicates that stress concentration effects are present. The dashed line shown in Figures 18 and 19 represents the Griffith relationship, i.e., the slopes of the lines are -0.5. It appears that significant deviation of the data from this line occurs below a notch size of around 2 mm, which is the same order of the predicted crack sizes given in Table 3.

The notched tensile data has also been used to calculate values of fracture toughness using equation 1, and the results are shown in Figures 20 and 21 for the two extremes of refining and wet pressing. The horizontal line shown in these figures is the value of fracture toughness measured using the in-plane tear tester, and we see that the calculated (uncorrected) values of fracture toughness are very much lower. However, if these values are corrected for stress concentration and size effects, they do approach and finally exceed the measured value with increasing notch size as shown in Figures 20 and 21. On the other hand, as the notch size approaches zero, the calculated values of fracture toughness begin to approach the same order of magnitude as the values shown in Table 3 where the assumption was made that the critical crack size is of the same order as the pore size at maximum frequency.

The southern pine handsheets had quite as high a tensile strength as the northern pine handsheets at a given level of densification; however, all of the property trends which were seen for the northern pine handsheets were in evidence for the southern pine handsheets. The correlation between specific tensile strength σ^* and the product of specific modulus E^* and fracture toughness G_c^* for the two pulps are compared below,

$$\text{Northern pine: } \sigma^* = 2.73(E^*G_c^*)^{0.607} \quad R^2 = 0.989$$

$$\text{Southern pine: } \sigma^* = 2.51(E^*G_c^*)^{0.687} \quad R^2 = 0.982$$

CONCLUSIONS

We have attempted to examine the tensile strength of paper within the framework of linear elastic fracture mechanics. An envelope for all of the properties examined, i.e., in-plane elastic constant, fracture resistance, pore size at maximum frequency, tensile strength and notched tensile strength was found, with the possible exception

of out-of-plane elastic constant, when paper was densified by different combinations of wet pressing and refining.

Fracture resistance was determined using a modified IPST in-plane tear tester, and values were found to be at the same level as those determined by Seth and Page (26). At the lowest level of refining and wet pressing, a small but significant amount of work is consumed in post fracture fiber pullout. Fracture resistance values calculated from notched tensile tests were much lower, but when corrected for size and stress concentration effects, a value was found at a certain notch size which equaled that determined using the quasi-static approach.

Attempts to use tensile strength, fracture resistance, modulus, and pore size data to form a correlation based on Griffith's equation were not successful. However, a good correlation was found between tensile strength σ and the product of fracture resistance G and modulus E of the form $\sigma = A(EG)^n$. This relationship would seem to imply that tensile strength is not dependent on crack size. On the other hand, the notched tensile results do show a sensitivity to single-edge notches particularly at the highest level of refining.

Griffith's equation was also used to estimate crack size using fracture resistance, modulus, and tensile data, and was found to be in the range of 1 mm to 2.5 mm. This might be interpreted as a formation effect or some form of distributed cracking as proposed by Zubelewicz and Bazant (45) for cement, i.e., a certain amount of pre-cracking of the material occurs before a crack can propagate. Tortuosity of the fracture path is one indication that formation might be an important factor. On the other hand, one would expect that the size, shape, and distribution of the pores in paper would be important determinants or, alternatively, that interfiber bond stress concentration is important, i.e., the Button effect. Further work is obviously required to resolve this paradox.

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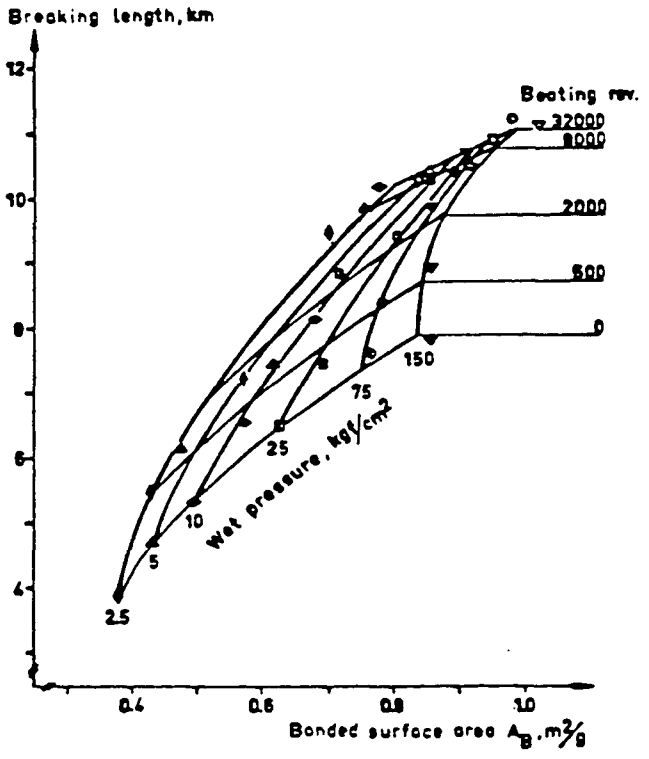

Figure 1: Tensile strength versus bonded area for different refining and pressing levels [taken from Rennel (1)]

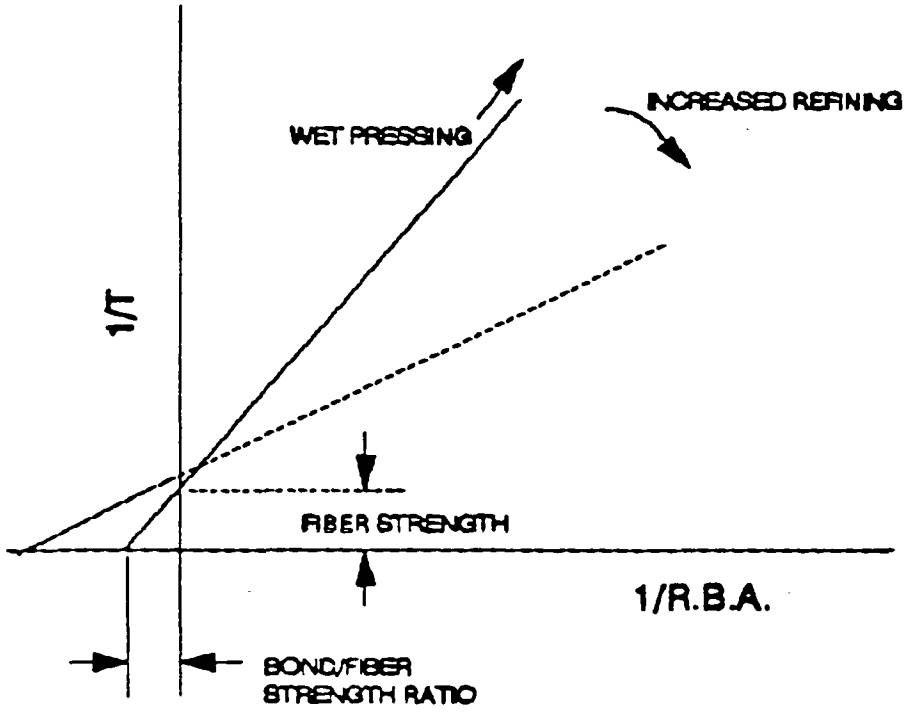

Figure 2: Graphical interpretation of Page's equation

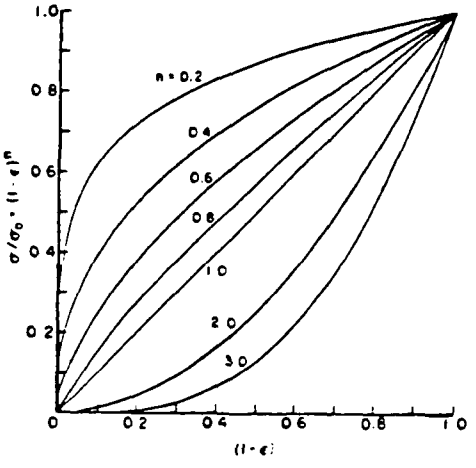

Figure 3: Modeling the tensile strength of paper as a voidal continuum

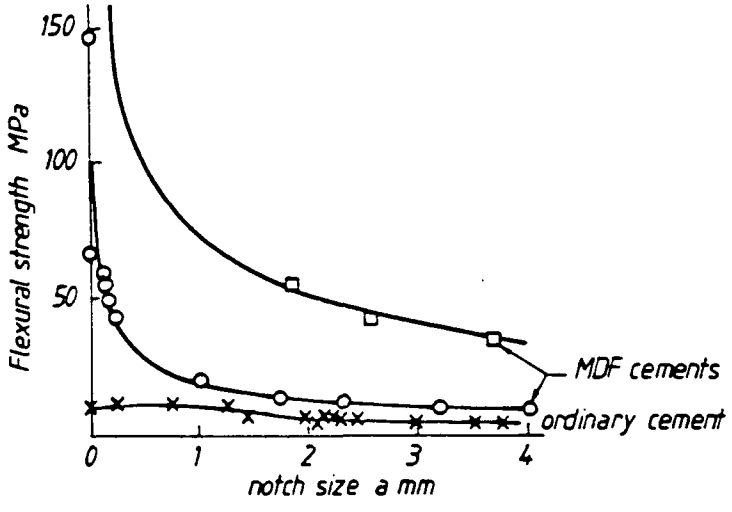

Figure 4: Bending strength versus crack size for three cements [taken from Birchall (20)]

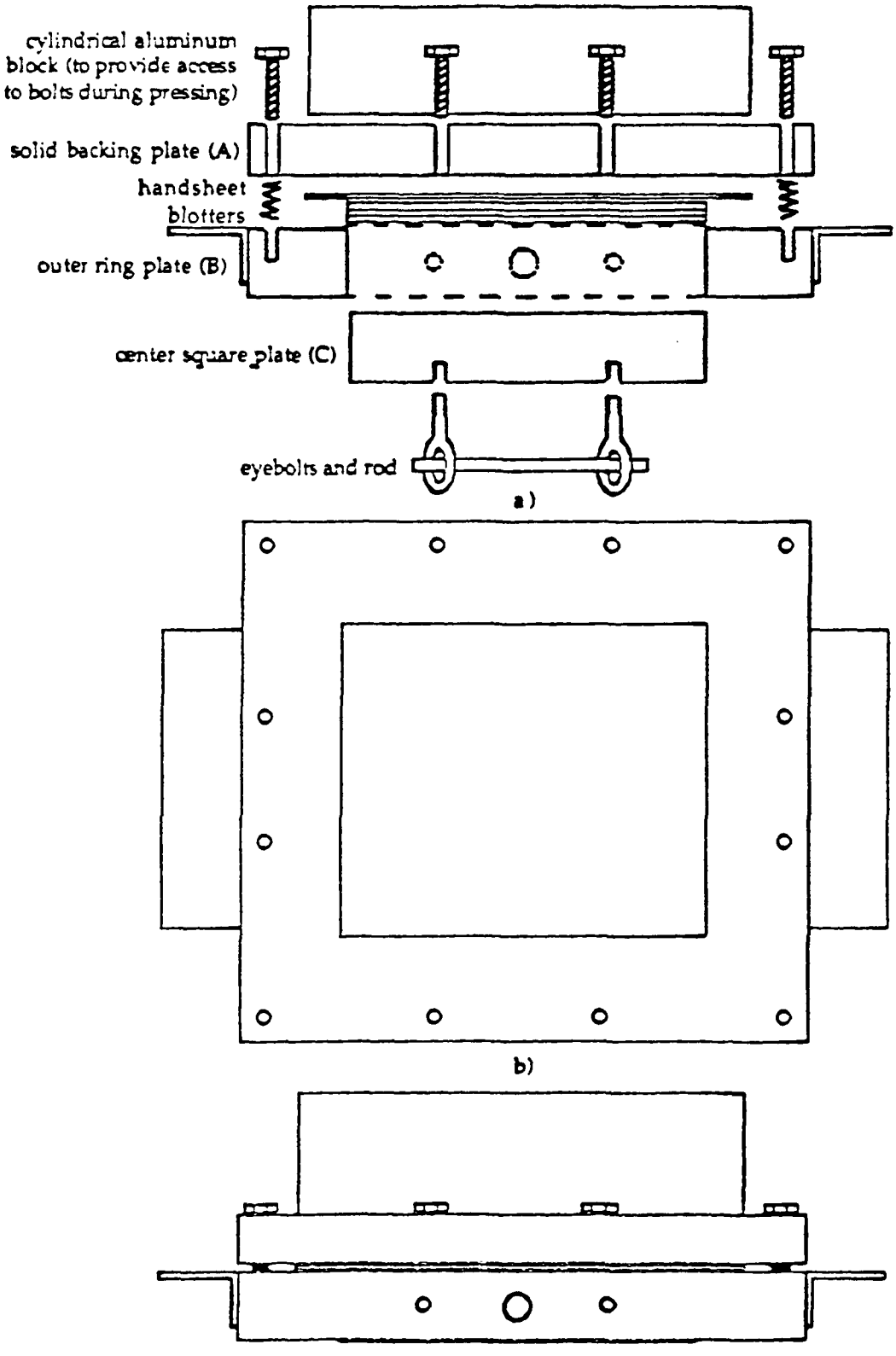

Figure 5: Restraint apparatus for wet pressing and drying

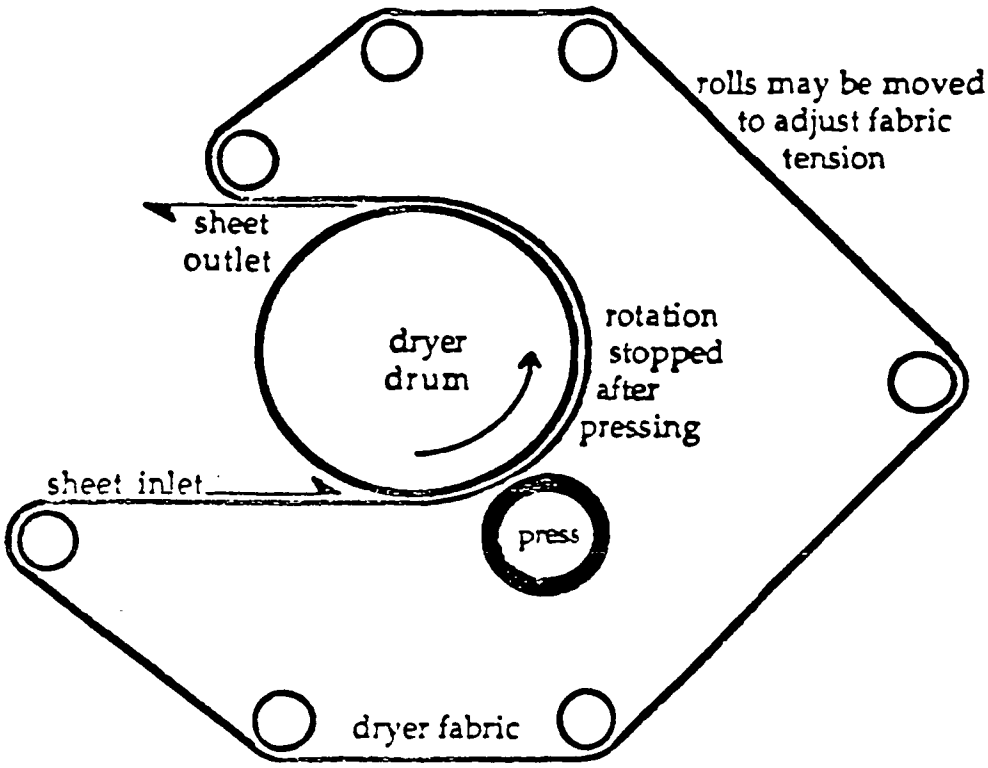

Figure 6: IPST press and dryer combination

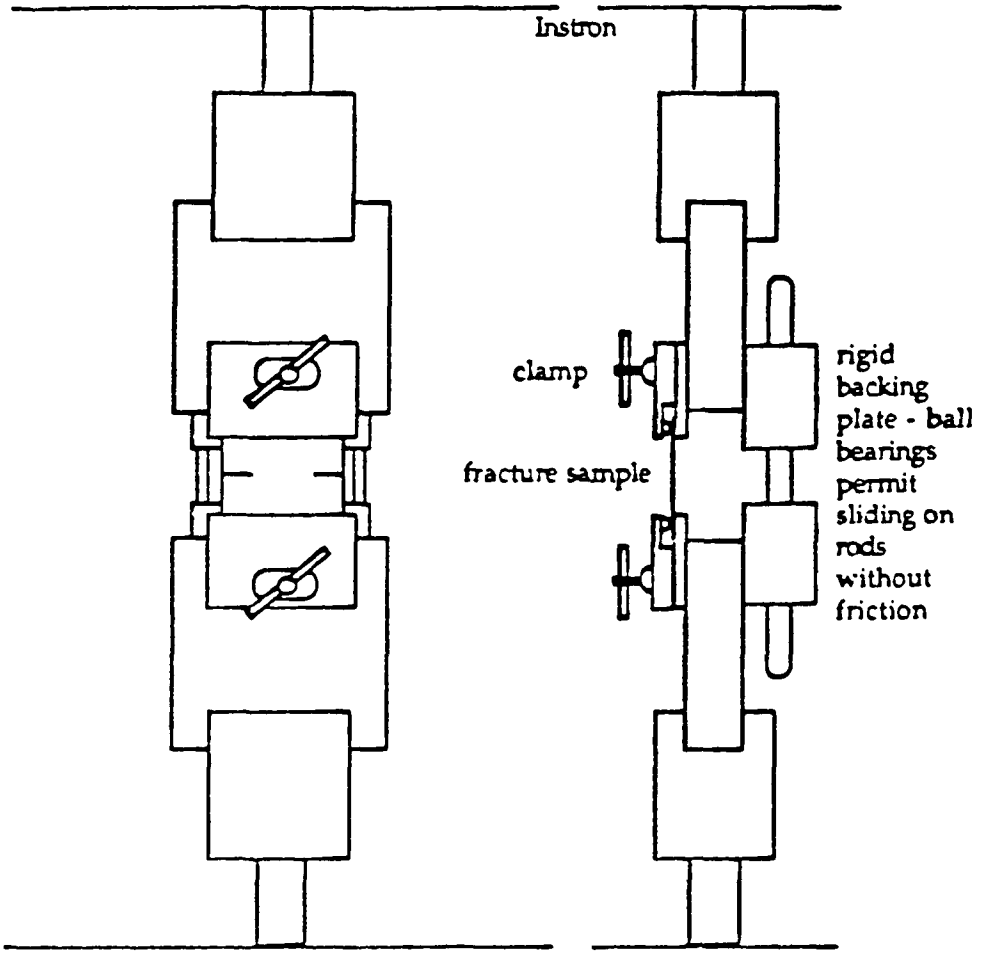

Figure 7: Modified IPST in-plane tear tester at 0^{o}

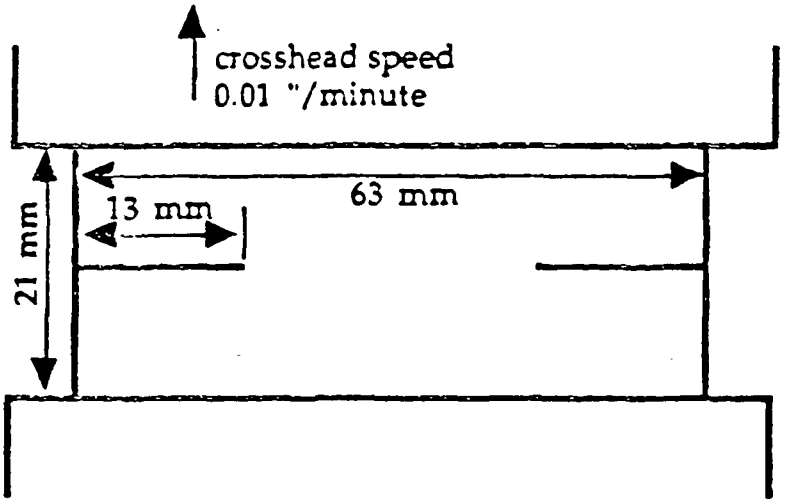

Figure 8: Single-edge notch sample and dimensions

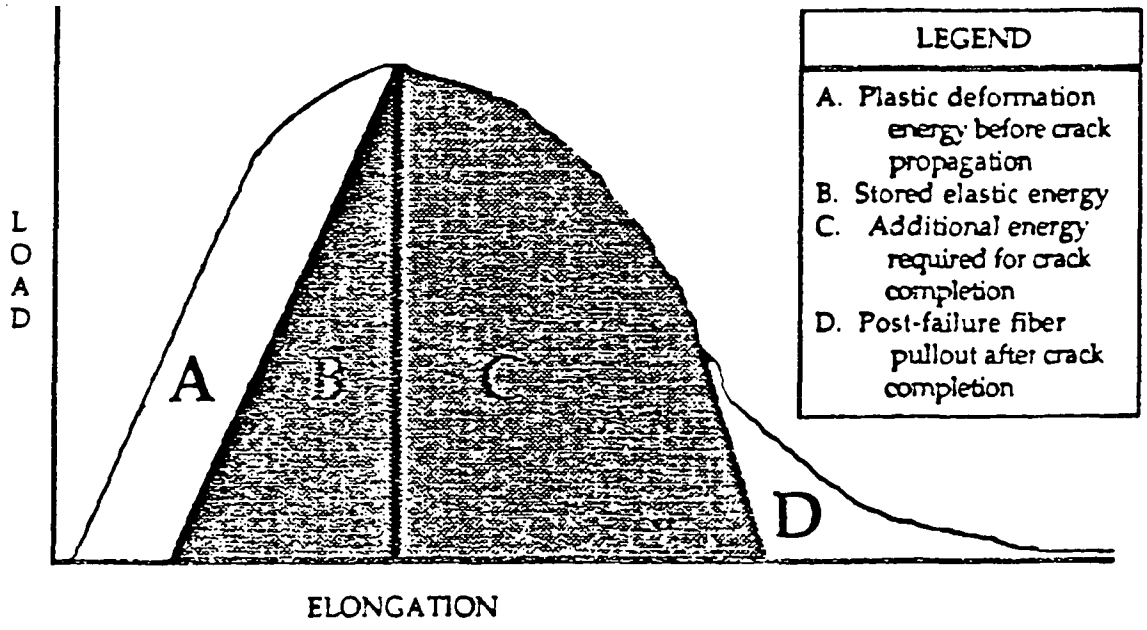

Figure 9: Tensile load elongation curve for fracture

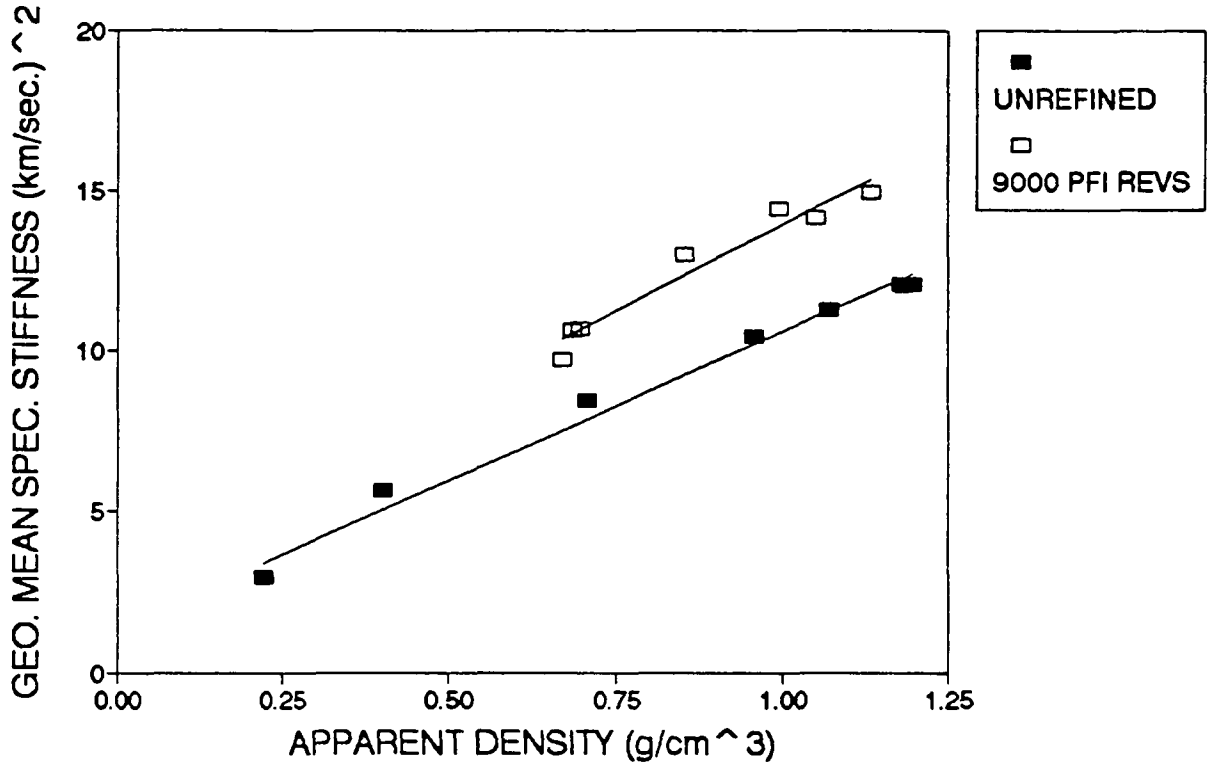

Figure 10: In-plane specific elastic constant versus apparent density

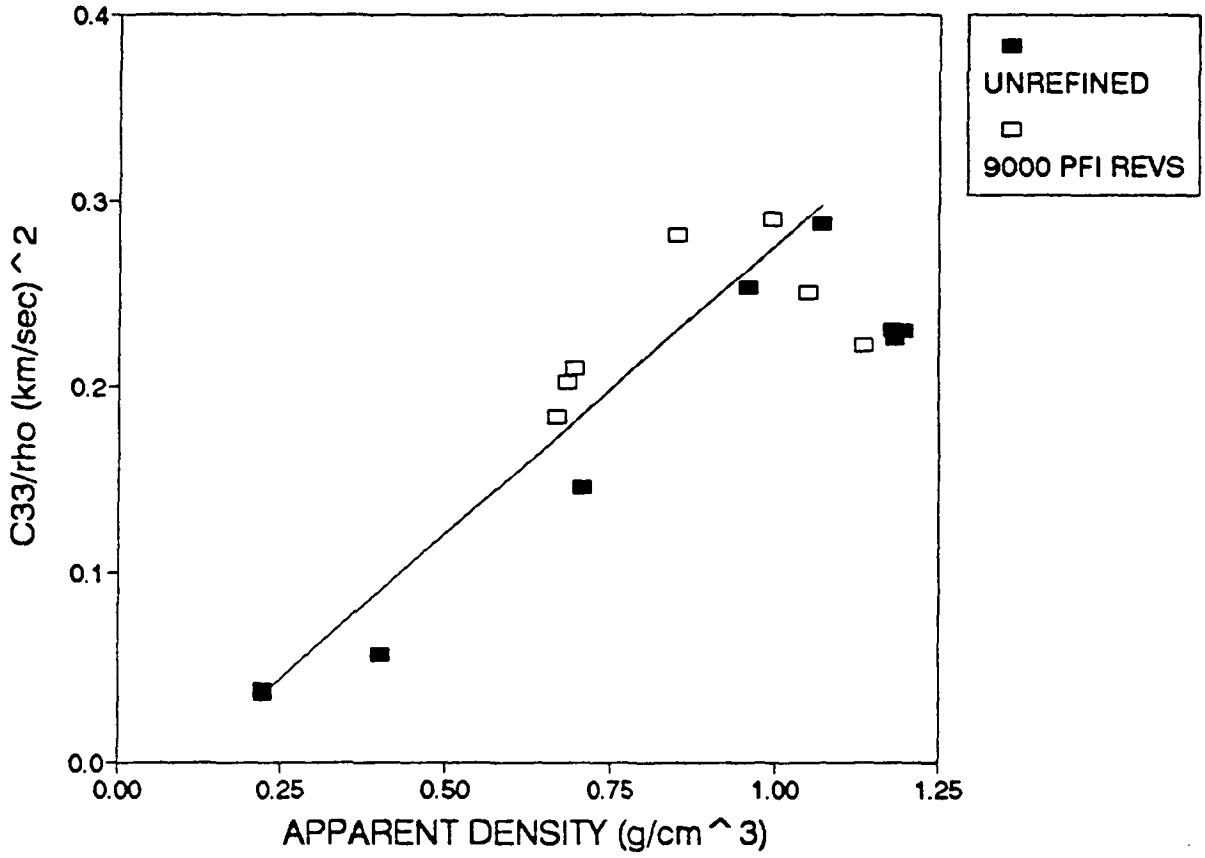

Figure 11: Longitudinal out-of-plane specific elastic constant versus apparent density

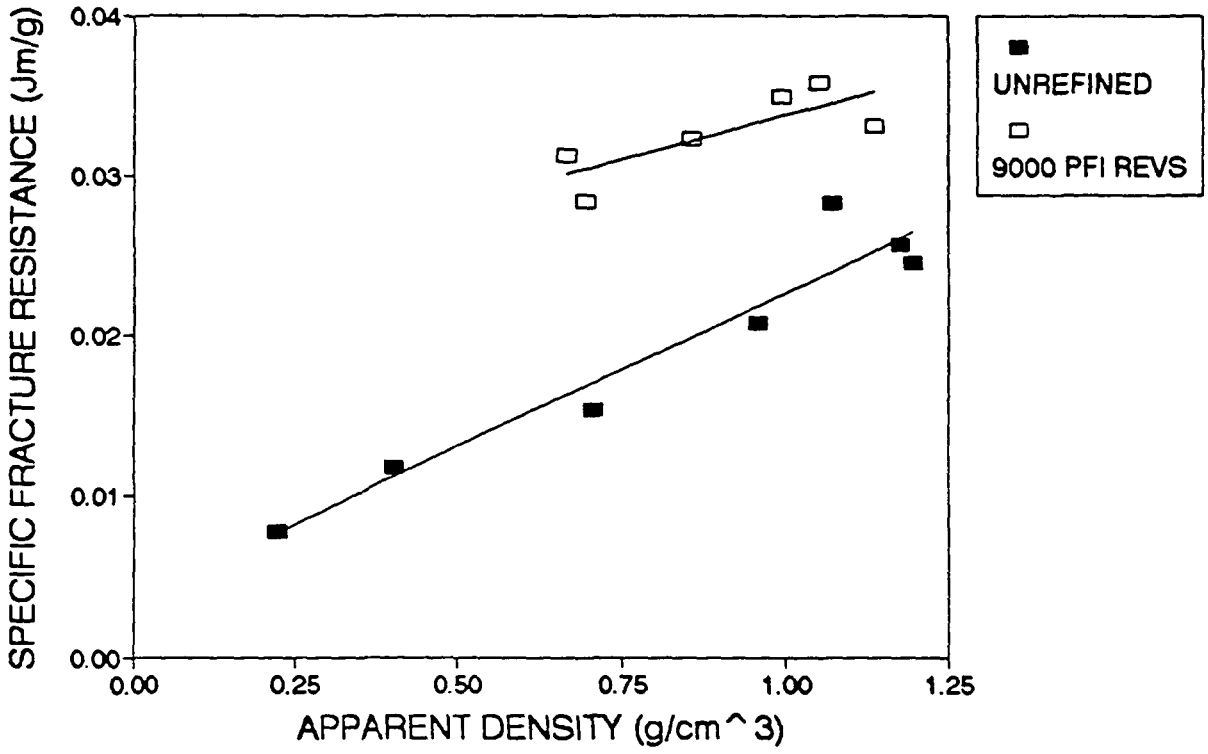

Figure 12: Fracture toughness versus apparent density

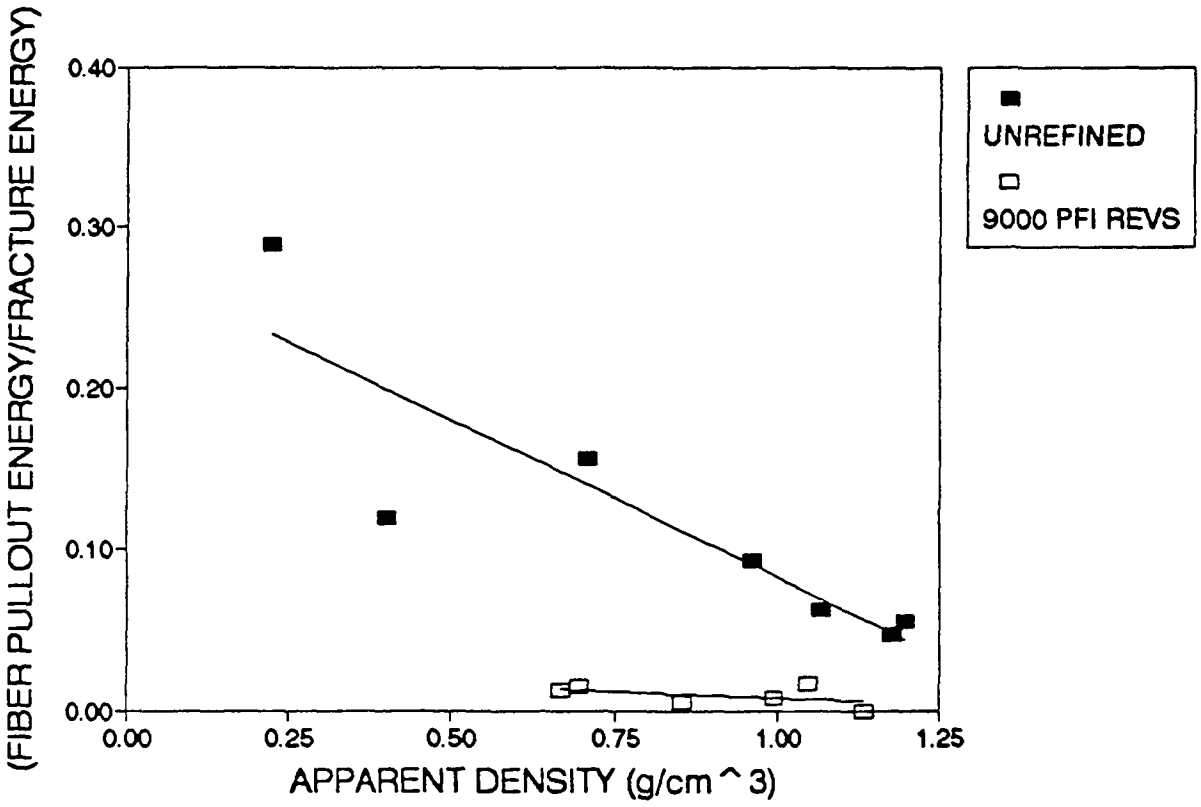

Figure 13: Work of fiber pullout

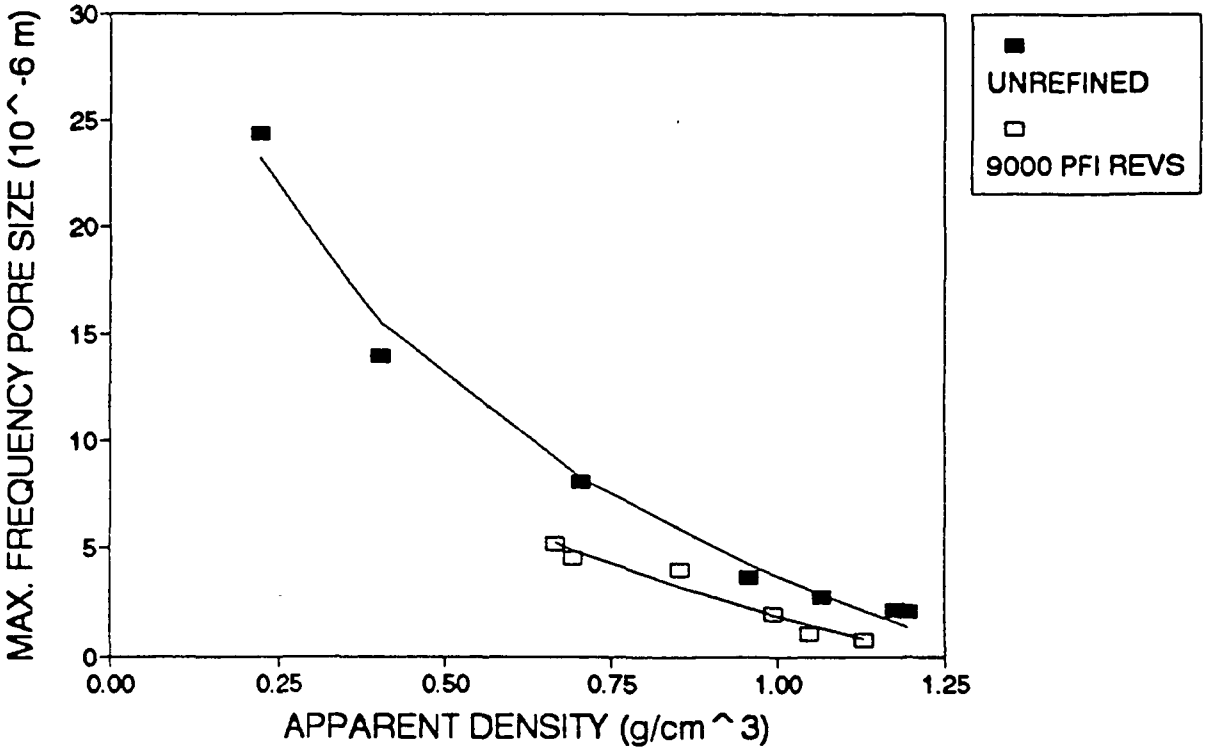

Figure 14: Pore size at maximum frequency versus apparent density

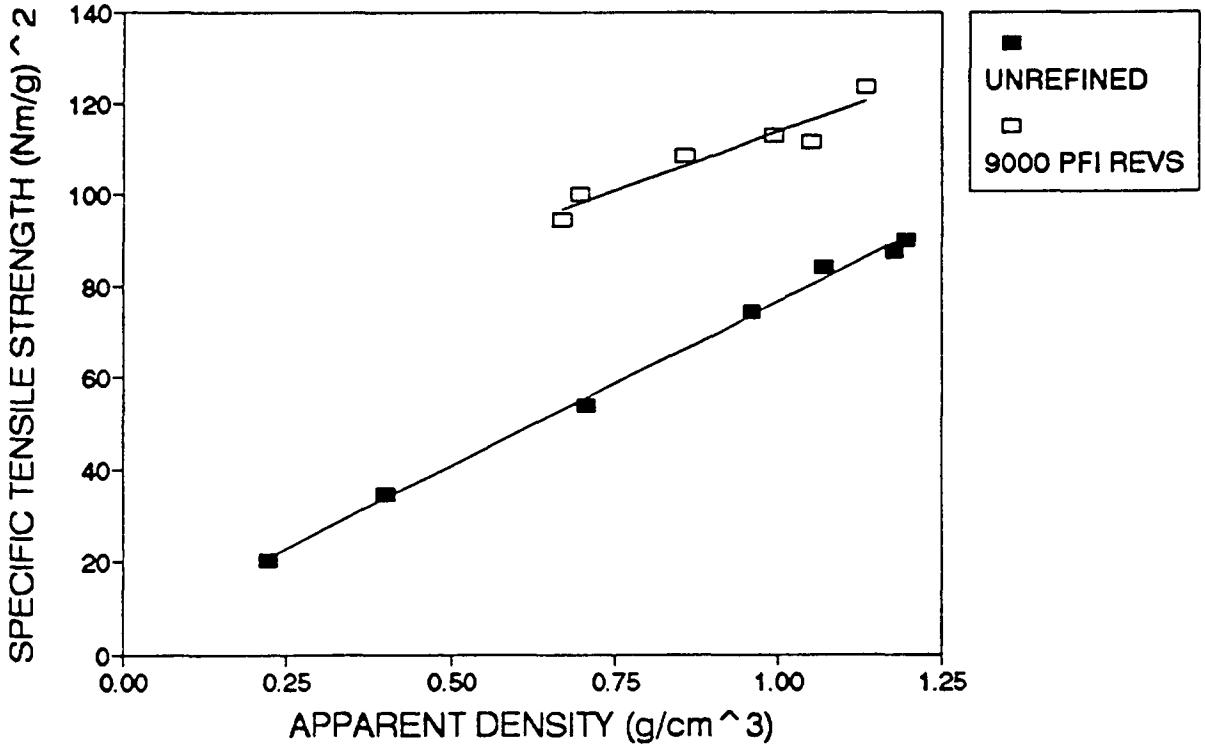

Figure 15: Specific tensile strength versus apparent density

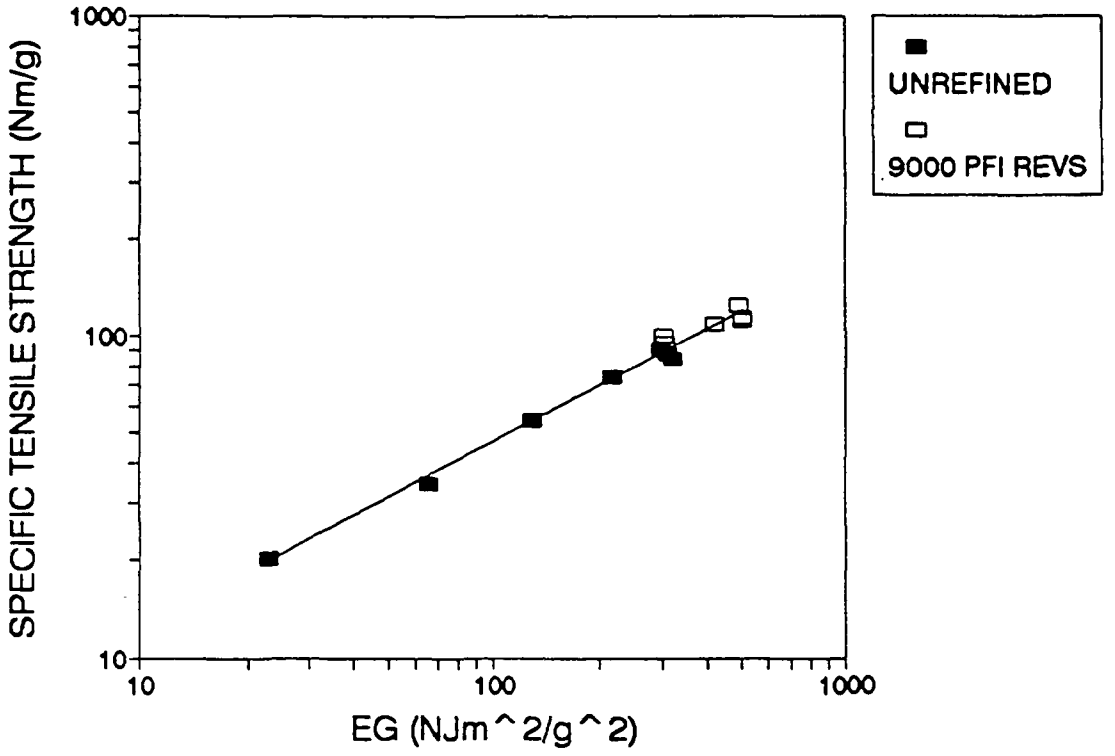

Figure 16: Specific tensile strength versus ($E^* \times G^*$)

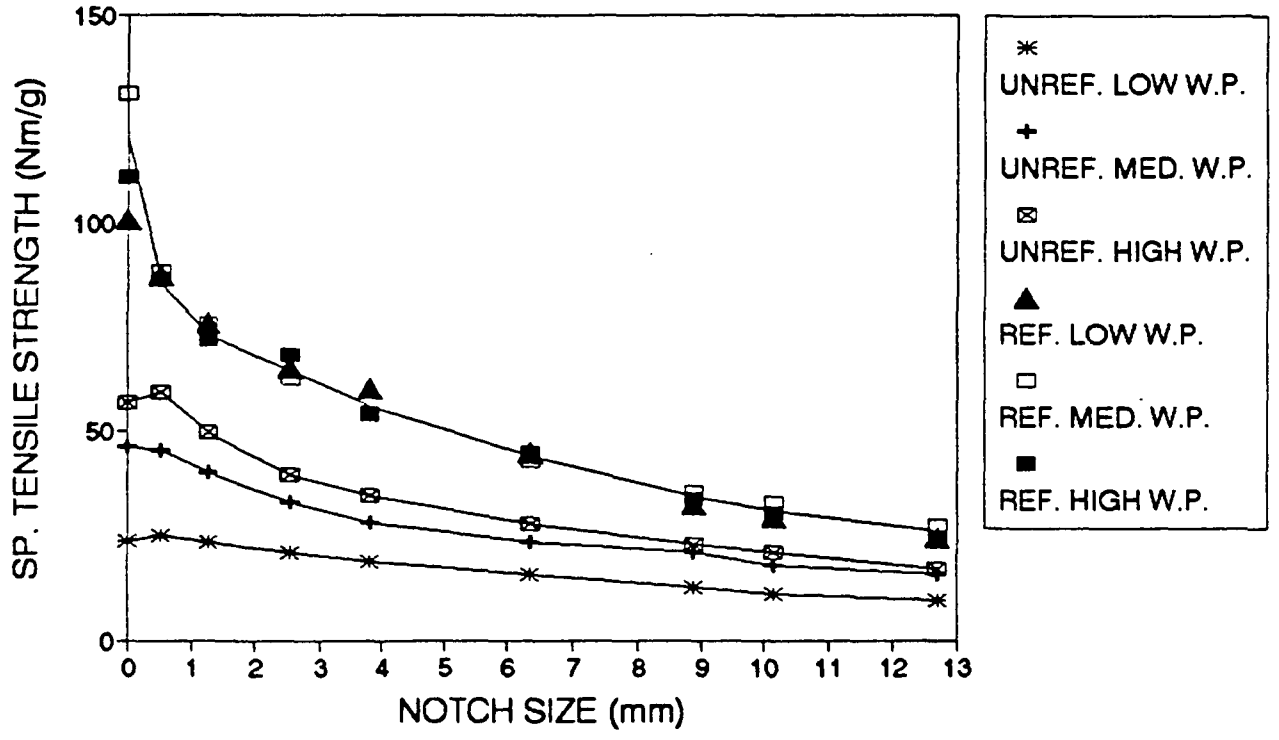

Figure 17: Specific tensile strength versus notch size

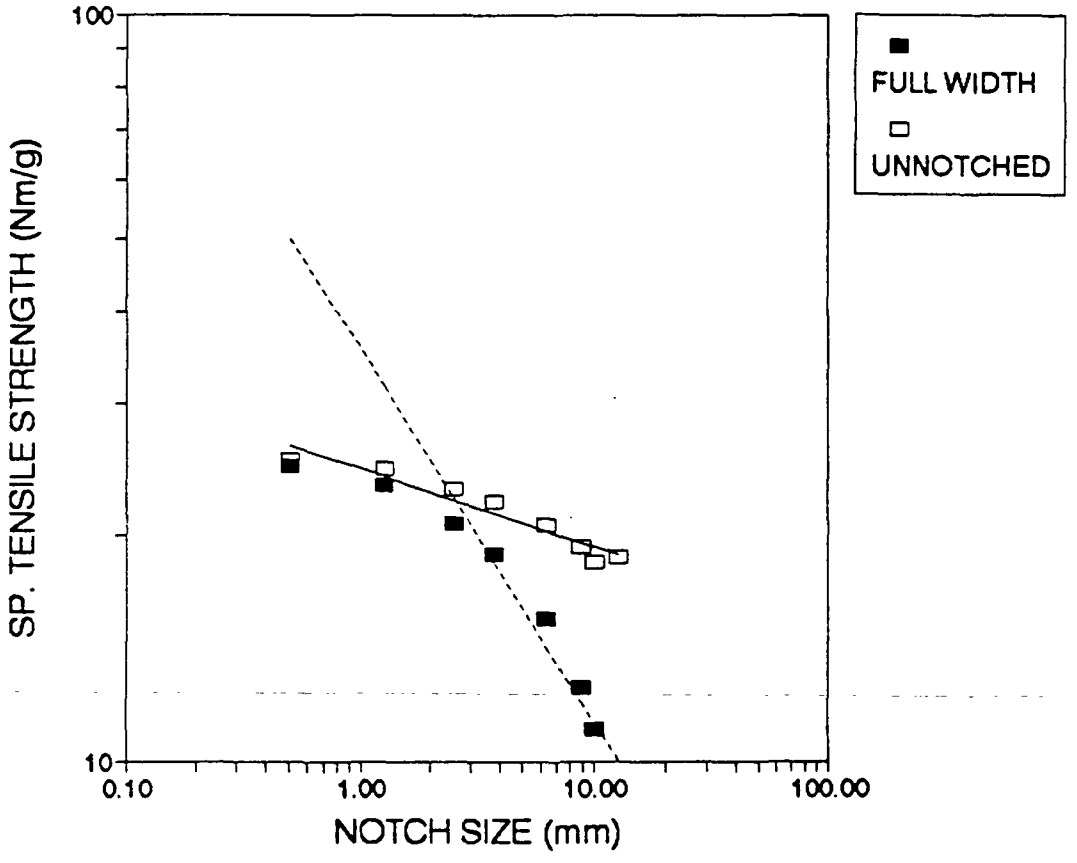

Figure 18: Log specific tensile strength versus log notch size (low level of refining and wet pressing)

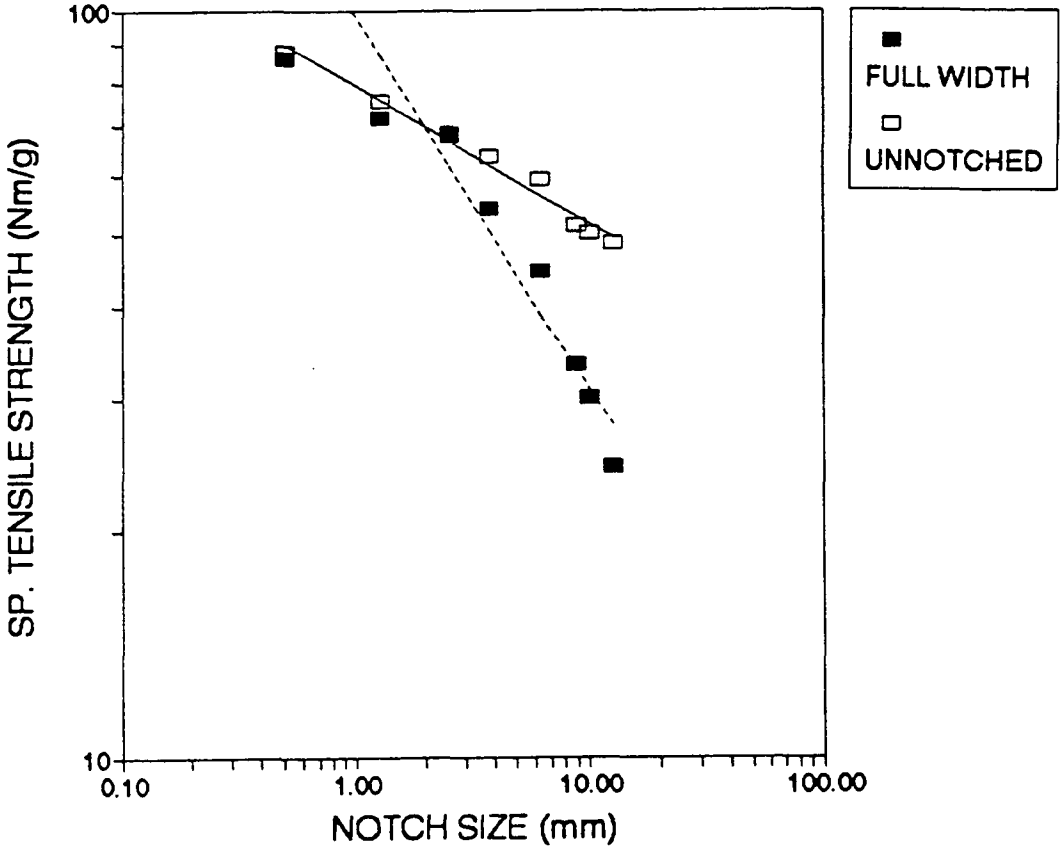

Figure 19: Log specific tensile strength versus log notch size (high level of refining and wet pressing)

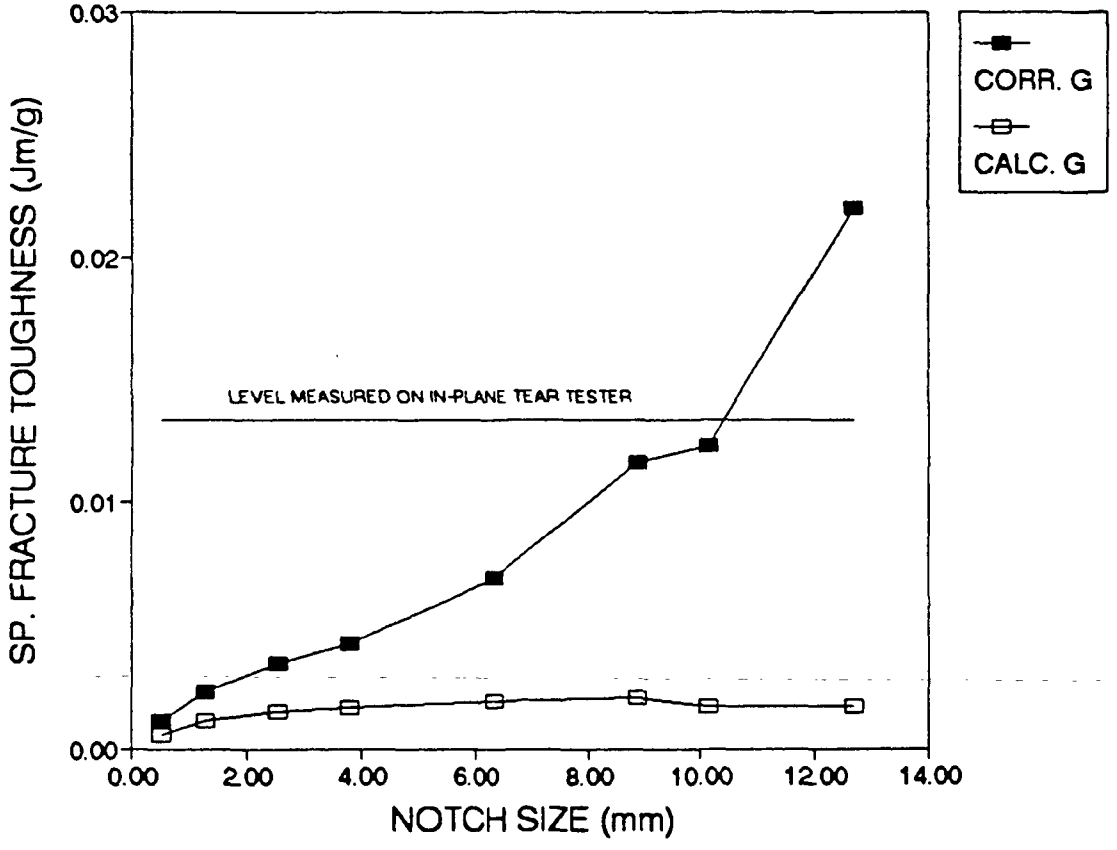

Figure 20: Comparison of measured and calculated fracture toughness values (low level of refining and wet pressing)

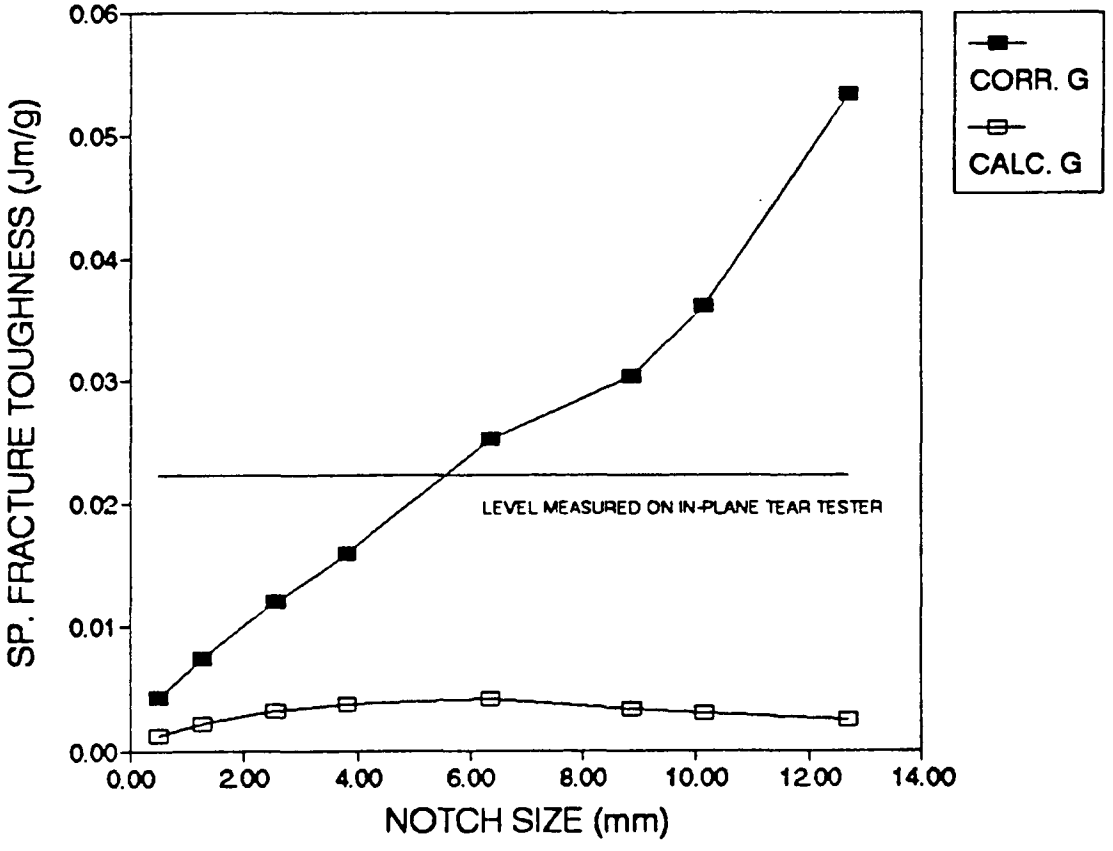

Figure 21: Comparison of measured and calculated fracture toughness values (high level of refining and wet pressing)